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UNCERTAINTY EVALUATION IN THE MEASUREMENT OF POWER FREQUENCY ELECTRIC AND MAGNETIC FIELDS FROM AC OVERHEAD POWER LINES

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Measurements of power frequency electric and magnetic fields from alternating current power lines are carried out in order to evaluate the exposure levels of the human body on the general public. For any electromagnetic field measurement, it is necessary to define the sources of measurement uncertainty and determine the total measurement uncertainty. This paper is concerned with the problems of measurement uncertainty estimation, as the measurement uncertainty budget calculation techniques recommended in standardising documents and research studies are barely described. In this work the total uncertainty of power frequency field measurements near power lines in various measurement sites is assessed by considering not only all available equipment data, but also contributions that depend on the measurement procedures, environmental conditions and characteristics of the field source, which are considered to increase the error of measurement. A detailed application example for power frequency field measurements is presented here by accredited laboratory.

INTRODUCTION

Serious public concerns are expressed about negative effects on human health as a consequence of exposure to electromagnetic fields. In the case of extremely low-frequency (ELF) fields, attention is focused on the alternating current (AC) power transmission systems, especially on high-voltage overhead lines, because of their significant field level. Many researchers[1–6] have been carrying out spot measurements of ELF electric and magnetic fields generated by AC power systems in living environments in order to evaluate public exposure. Measurement procedures with regard to exposure of human beings have been established by the IEC 61786:1998, IEC 62110:2009 and Institute of Electrical and Electronics Engineers (IEEE) 644-1994 Standards[7–9]. Furthermore, while performing such measurements, it is important to use field meters that are suitable for outdoor measurements and meet, at least, the requirements of Standards mentioned above. The measurement results are compared with the human exposure limits such as International Commission on Non-Ionizing Radiation Protection Guidelines and IEEE Standard[10, 11].

A measured value is only complete if it is accompanied by a statement of the associated uncertainty, because all measurements are subject to uncertainty. In addition, the evaluation of uncertainty becomes crucial when assessing a compliance with exposure guidelines or limits. Although it is necessary to determine the measurement uncertainty, several problems appear during its estimation.

First, the main problem is the identification and quantification of the different uncertainty components. The mechanisms that can cause errors during the ELF field measurement are many, particularly for the measurement of electric field. Sources of uncertainty, that should be considered, are given in Table 1. Moreover, in the case of power frequency field measurement in the vicinity of an overhead transmission line, high uncertainties can appear when measuring highly non-uniform fields in complex environments. It is possible to obtain a total uncertainty value higher than 10 %. Finally, the measurement uncertainty estimation can become absolutely impossible under specific circumstances in various environments.

The related Standards[7, 9] provide, among other, guidance on how sources of uncertainty during calibration and measurements should be combined to determine total measurement uncertainty. Furthermore, the Guide to the Expression of Uncertainty in Measurement (GUM)[12] and the United Kingdom Accreditation Service (UKAS) Publication M3003[13] contain extended instructions on the calculation of the uncertainties of measurements. However, few research studies[14, 15] contain instructions on the calculation of the uncertainties of power frequency field measurements under high-voltage power lines taking into account uncertainty components with reference to both the measuring instruments used and the measurement procedures and conditions.

Considering the specialties of measurements of low-frequency magnetic and electric fields with regard to exposure of human beings, an assessment of

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Table 1. Sources of measurement uncertainty.

Electric field	Magnetic field
Calibration	Calibration
Non-uniform electric field	Non-uniform magnetic field
Asymmetry in probe design	Orthogonality of three-axis coils
Pass-band limitations	Pass-band limitations
Noise floor	Noise floor—crosstalk
Handle leakage	Instrument time constant
Field meter inclination and reading errors	Separation of sensors
Positioning the probe	Positioning the probe
Presence of objects	Presence of ferromagnetic or conductive objects
Observer proximity effects	Proximity of batteries
Location of measurement	Location of measurement
Temperature and humidity	Temperature and humidity
Electromagnetic immunity	Electromagnetic immunity
Background electric field	Background magnetic field
Long-term drift	Long-term drift

the associated uncertainties is presented in this work. Also, for the purpose of this document, the above difficulties in the measurement uncertainty evaluation, which occur from power lines depending on the type of measurement site, are examined. An extensive uncertainty calculation technique is applied on the case of power frequency field measurements near power systems by the accredited High-Voltage Laboratory (HVLab) of the National Technical University of Athens (NTUA).

MEASUREMENTS

Measuring instrument

The field measurement equipment used in this work fulfils the instrumentation requirements set by the IEC 61786 and IEEE 644-1994 Standards(7, 9). Due to the harmonic content of electric and magnetic fields produced by AC power systems, the pass band of the related equipment should extend from the fundamental frequency (50 Hz) to the first few harmonics (500 Hz). According to the Standards(7, 9), a narrower pass band may be used for the field measurement from power transmission lines where the harmonic content is small.

The measuring instrument employed here is a Narda EFA-300 Field Analyzer designed for standardised measurement of alternating electric and magnetic fields over the frequency range of 5 Hz to 32 kHz with an uncertainty of ± 3 %(16). This uncertainty value includes all partial uncertainties (absolute error, linearity, frequency response and isotropy) as well as temperature- and humidity-related deviations. The instrumental uncertainty is increased if the measured levels for electric and magnetic fields are >5 V m^{-1} and 40 nT, respectively. For measuring electric and magnetic fields, it is equipped with both external, isotropic electric and magnetic field probes (B-field 100-cm^2 probe and E-field module). The meter is also calibrated to indicate the rms value of the power frequency electric and magnetic fields.

Measurement procedures

Measurements of the rms values of the resultant electric and magnetic fields generated by overhead power lines were made with the three-axis instrument mentioned earlier. Both wideband (from 5 Hz to 32 kHz) and selective (at the fundamental frequency of 50 Hz) field measurements were performed, although the measurement results were negligibly different, since the harmonic content is sufficiently small near power lines.

Power frequency field measurements were carried out according to standard procedures(8, 9). Specifically, the electric field strength and magnetic flux density were measured at a height of 1.0 m above the ground level at selected positions at suitable intervals in the area of interest. At each measurement location the measurements were performed within the area enclosed by two towers and their respective right-of-way (ROW). After the initial survey of the measurement location, at a minimum one lateral and one longitudinal measurement lines were identified to perform the electric and magnetic field measurements. First, the magnetic field measurements were performed at all the measurement points in both the lateral and longitudinal test lines. After completion of the magnetic field measurements, electric field measurements were performed at all measurement points in a measurement line.

At each measurement point the electric and magnetic fields were measured for a minimum measuring time of 5 min. The electric and magnetic field data were collected repeatedly every 30 s during the 5-min minimum time period. Therefore, in each measurement point, 10 measurement values of the electric field strength and magnetic flux density have been taken for both Broadband and Bandpass cases.

Also, the method was different for electric and magnetic field measurement. During the measurement of electric field the distance between the electric field meter and operator was at least 5 m to achieve an error of <1 %. A fibre-optic link, which connected the probe to the display unit, was used to assure this distance. Additionally, the probe was introduced into the electric field on an insulating tripod. Compared with the electric field measurement procedure, the magnetic field probe during the measurement of magnetic field was directly connected to the EFA-300 base meter held by the observer, as the observer proximity effects are negligible. In both cases, care was taken to prevent interference caused by the proximity of

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permanent and movable objects during the field measurement in order to minimise the measurement uncertainty values(7–9).

Measurement locations

Measurements of power frequency electric and magnetic fields were performed in the vicinity of the 150- and 400-kVAC overhead power lines used in Greece. Electric and magnetic field measurements were made at plenty measurement locations and grouped in Table 2.

The grouping was made because of differences in the characteristics of the various environments such as population density, surface roughness, objects and other sources of power frequency fields near the measurement points. Subsequently, one expects the process of measurement uncertainty estimation to be different in the various measurement sites.

Table 2. Characteristics of measurement locations.

Measurement locations	Characteristics
Residential area (urban area, suburbs)	High population density Full of objects Low surface roughness Several other sources of power frequency fields
Open land (rural area, countryside)	Low population density Free of objects Flat ground surface A few other sources of power frequency fields
Hilly or mountainous regions	Zero population density Vegetation (trees or tall grass) Very rough terrain No other sources of power frequency fields

Measurement results

An example of measurement results of electric and magnetic fields generated by a 150-kV double-circuit overhead line, untransposed phase sequence, vertical configuration, balanced currents of 168 and 160 A in each circuit, and a span of 330 m (between the AX7NA and AX8NA towers) in a residential area is presented below. This example was chosen, because of the great interest as the measurements were carried out in public accessible areas and the influence on the measurement results, due to nearby objects (cars, metal fences, vegetation, etc.) and fields from other power-frequency sources (low and medium voltage power lines), were significant.

The measurements of electric and magnetic fields were performed at 63 points in 3 measurement lines in the measurement area. In particular, the field was measured along two lines perpendicular to the overhead line, which cut the x axis at the coordinates $x_1 = -35$ m (measurement line Lat-1) and $x_2 = 60$ m (measurement line Lat-2). Also, in this example electric and magnetic field measurements were performed along the measurement line parallel to the overhead line just below the electric line axis (measurement line Lon-1).

The sketch of the measurement site is shown in Figure 1. Also, in the below sketch the measurement lines where the measurement was carried out are specified.

In addition, the drawings below (Figures 2 and 3) detail the configuration of the power lines, the

Figure 1. A sketch of the measurement site.

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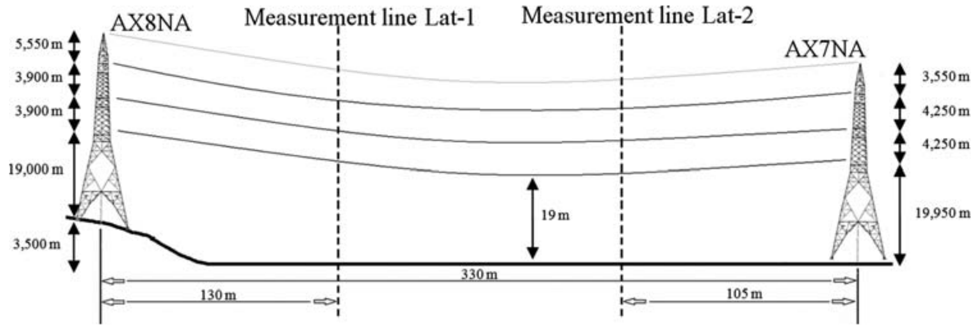

Figure 2. A side view of the measurement area.

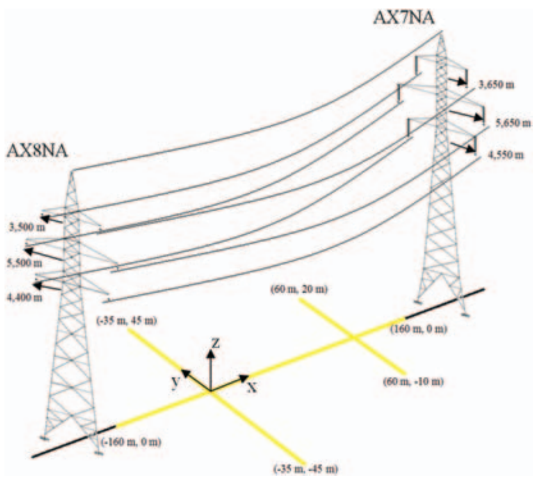

Figure 3. An isometric view of the measurement area.

coordinates of the conductors, the location of the measurement lines and the ground surface roughness.

Figures 4–6 present the measurements of the electric and magnetic fields for each position at a height of 1.0 m above the ground level for the EFA-300 instrument. In these figures the results for the bandpass filter are presented. All the instrument correction factors have been applied. Also, it is noted that the readings of magnetic field are related to the time of day, when measurements are performed and hence, to the load on the line, because load currents fluctuate considerably during the day.

The uncertainty in the measured electric and magnetic fields was indicated at each measurement point with a vertical error bar. This error bar represents the total uncertainty, which was computed using the appropriate uncertainty components that will be soon described in the following section.

At first, electric and magnetic field levels measured at measurement line Lon-1 with appropriate intervals of 10 m are given in Figure 4. The highest electric field level (823 V m^{-1}) was observed 60 m away from the mid-span because at the measurement points near the mid-span, the electric field was reduced by the buildings and other objects. As the measurement point was moved away from mid-span toward one of the towers, the electric field was substantially reduced, due to the increasing height of the conductors above the ground and the presence of the tower. Also, it was proved that a significant decrease in the field level occurred as the tower was approached. In contrast, the magnetic field level varied with the height of the conductor, and therefore, the maximum value of the magnetic field (893 nT) along the measurement line was found at the lowest sag point 40 m away from the mid-span.

Additionally, the results of the measurement of electric and magnetic field levels at measurement line Lat-1 are given in Figure 5. The measurements were made to a lateral distance of 45 m on both sides of the ROW. The maximum value of the electric field (610 V m^{-1}) was found to be 2.5 m away from the line axis, because the overhead transmission line is close to tall buildings at the left side of the profile. Thus, as a result of buildings' vicinity, the electric field levels at the right side of the profile were significantly higher than the left side. As for magnetic flux density, the highest magnetic field level (825 nT) was located at the position under the circuit with the higher load current. The magnetic field level decreased quite rapidly as the distance from the line axis increased.

In the same way, Figure 6 shows the lateral profiles of the electric and magnetic fields generated by the overhead transmission line at measurement line Lat-2. The measurements were made to a lateral distance $<$30 m beyond the outside conductors, as IEEE Standard[11] suggests, due to vegetation and terrain conditions. At this lateral profile, the highest electric (833 V m^{-1}) and magnetic (880 nT) field levels were found to be under the 150-kV double circuit power line. Normally, as the depth distance increases, the electric and magnetic fields decrease.

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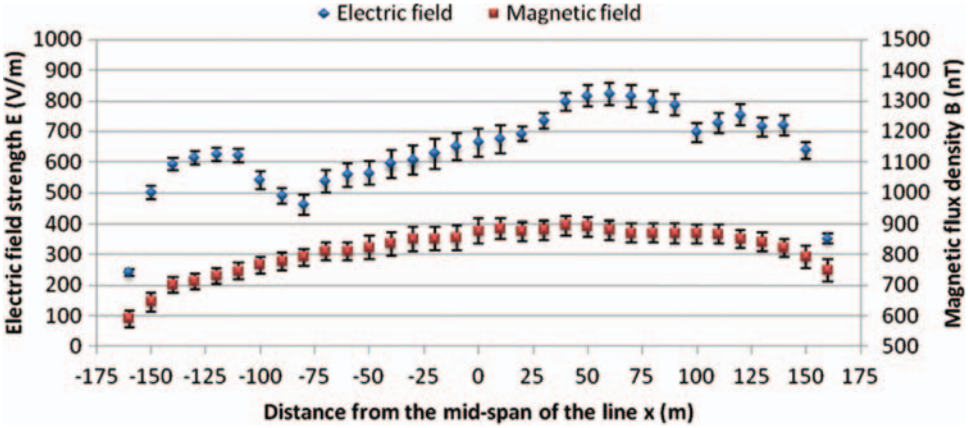

Figure 4. A longitudinal profile of electric and magnetic fields under the overhead transmission line (measurement line Lon-1).

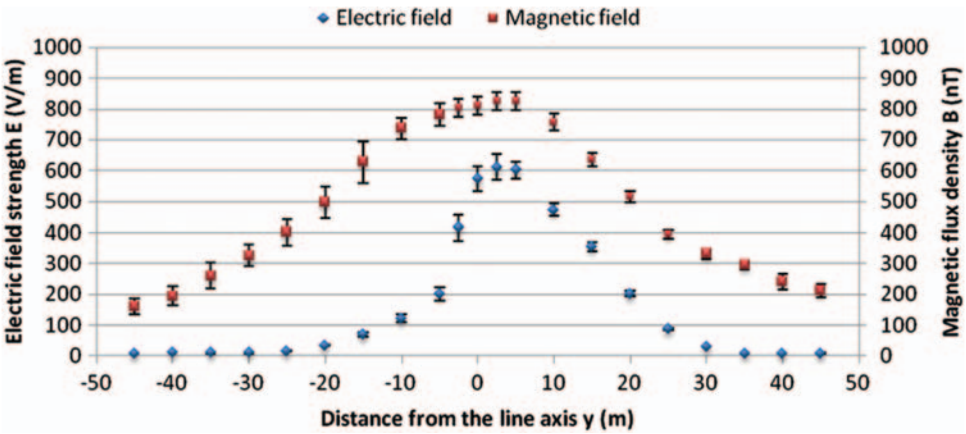

Figure 5. A lateral profile of electric and magnetic fields under the overhead transmission line (measurement line Lat-1).

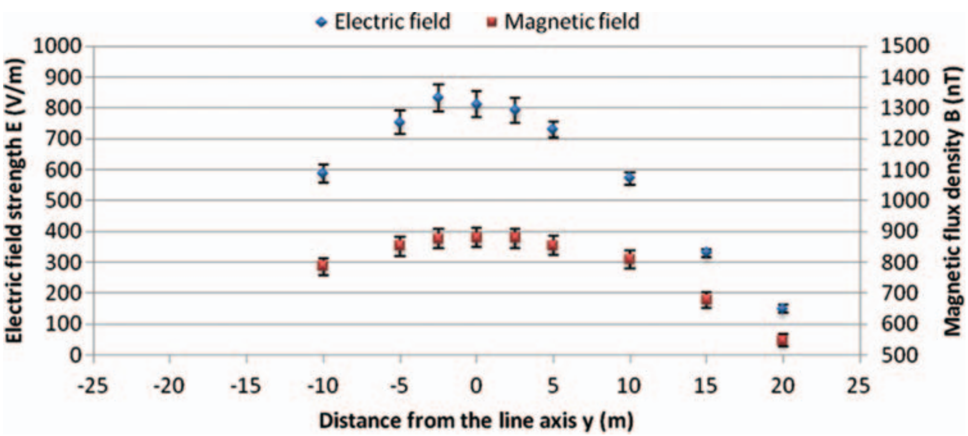

Figure 6. A lateral profile of electric and magnetic fields under the overhead transmission line (measurement line Lat-2).

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UNCERTAINTIES CALCULATION

Theoretical background

In general, the uncertainty of a measurement consists of many components, which can be classified into two types, depending on the way of their calculation. *Type A* uncertainty is evaluated using statistical analysis of a series of observations, while *Type B* is calculated using any information available, concerning the variability of the measured quantity, such as calibration certificates, former measurements data, measuring equipment specifications, operational procedure, experience and subjective judgement of the person making the measurements[12, 13].

The combined standard uncertainty derives from the combination of all individual components, taking under consideration the probability distribution of each. Following the International Organization for Standardization (ISO) Guide[12], a general equation of the combined standard uncertainty can be written in the form:

$$u_{\mathrm{C}}(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i}\right)^2 u^2(x_i)} = \sqrt{\sum_{i=1}^{N} c_i^2 u^2(x_i)} = \sqrt{\sum_{i=1}^{N} u_i^2(y)} \qquad (1)$$

where the estimate of the measurand $y(x_1, x_2, \ldots)$ is a function of several observations or estimates x_1, x_2, .. , $u(x_i)$ are defined standard uncertainty of entry estimates and c_i are called sensitivity coefficients. Practically, the sensitivity coefficients describe how the estimate of y varies with changes in the input estimates x_1, x_2, etc.

In this paper, Type A uncertainty is computed via statistical analysis of series measurements (repeatability), using the following equation:

$$u_{\mathrm{A}} = \frac{s_{\mathrm{A}}}{\sqrt{n_{\mathrm{A}}}} = \sqrt{\frac{1}{n_{\mathrm{A}} \cdot (n_{\mathrm{A}} - 1)} \sum_{i=1}^{n_{\mathrm{A}}} (x_i - x_{\mathrm{m}})^2} \qquad (2)$$

where n_{A} is the number of the repeated field measurements at each measurement point, x_i the measured value, x_{m} the mean value of the n_{A} measurements and s_{A} the standard deviation from the mean value.

Knowing the distribution followed by each source of uncertainty, uncertainty Type B is calculated as shown in the following equation, U_{B_i} being the contribution of each uncertainty source:

$$u_{\mathrm{B}} = \sqrt{\sum_{i=1}^{N} u_{\mathrm{B}_i}^2} = \sqrt{\sum_{i=1}^{N} \left(\frac{s_{\mathrm{B}_i}}{k_i}\right)^2} \qquad (3)$$

where s_{B_i} is the limit value of source i, and k_i is the coverage factor of the corresponding distribution (divisor). Usually, it is assumed a rectangular or uniform probability distribution, with a divisor equal to $\sqrt{3}$ or 2, respectively.

The combined standard uncertainty is calculated as a combination of uncertainties Type A and Type B, by means of the following equation:

$$u_{\mathrm{c}} = \sqrt{u_{\mathrm{A}}^2 + u_{\mathrm{B}}^2} \qquad (4)$$

The expanded uncertainty will be as in the following equation:

$$U = k \cdot u_{\mathrm{c}} \qquad (5)$$

For a coverage probability of 95.45 %, the coverage factor will be $k = 2$.

Uncertainties calculation

As described in the sub-section 'Measurement procedures' of the present paper, for each point five repetitive measurements were taken in order to evaluate the type A uncertainty. All measurements for a measurement point under an overhead power line were carried out within 10 min to obtain the set of measurement results with little fluctuations in the load current. Also, the electric field levels generated by an overhead line hardly change, because the voltage of the overhead line is almost stable. Due to these facts, the uncertainty Type A was considered negligible.

In this paper, the evaluation of uncertainty was performed following the ISO Guide and UKAS Publication M3003[12, 13]. The uncertainty budgets for both the electric and magnetic field measurements are summarised in Tables 3 and 4, which report for each uncertainty component the associated uncertainty value, distribution of probability, divisor, sensitivity coefficient and standard uncertainty. The standard uncertainty is calculated by dividing the uncertainty value with the respective divisor, which depends on the probability distribution of the partial uncertainty contributor. Each partial uncertainty's contribution to the combined standard uncertainty is just the square of the standard uncertainty multiplied by the square of the relevant sensitivity coefficient. All the sensitivity coefficients are equal to 1, resulting from the linear functional relationship between the input quantities on which it depends and the measurand[15].

The sources of uncertainty are divided into four categories namely 'field source', 'measurement equipment', 'measurement procedure' and 'environmental conditions'. Also, it is assumed that the uncertainties from different categories are uncorrelated.

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Table 3. Uncertainty budget for the electric field strength measurements.

Source of uncertainty	Estimation technique	Uncertainty value (%)	Probability distribution	Divisor	Sensitivity coefficient	Standard uncertainty (%)
Field source						
Non-uniformity of the field	Operator's judgement	0	Normal	1	1	0
Measurement equipment						
Calibration uncertainty	Calibration certificate	1	Normal	2	1	0.5
Uncertainty of the field meter/probe	Manufacturer data sheet	3	Rectangular	$\sqrt{3}$	1	1.73
Noise	Manufacturer data sheet	0	Normal	1	1	0
Measurement procedure						
Positioning uncertainty of the probe	Operator's judgement	≈0	Rectangular	$\sqrt{3}$	1	0
Uncertainty due to orientation of the probe	Operator's judgement	≈0	Rectangular	$\sqrt{3}$	1	0
Environmental conditions						
Temperature and humidity	Manufacturer data sheet	0	Rectangular	$\sqrt{3}$	1	0
Proximity effects of operator	Operator's judgement	1	Rectangular	$\sqrt{3}$	1	0.58
Proximity effects of objects	Operator's judgement	0–10	Rectangular	$\sqrt{3}$	1	0–5.77
Background fields	Operator's judgement	0–5	Normal	2	1	0–2.5
Combined standard uncertainty, $u_c = \left(\sum u_i^2\right)^{1/2}$ (%)						1.80–5.60
Expanded uncertainty (normal distribution), $U_E = k \cdot u_c$ (for k=2)						3.60–11.21

Table 4. Uncertainty budget for the magnetic flux density measurements.

Source of uncertainty	Estimation technique	Uncertainty value (%)	Probability distribution	Divisor	Sensitivity coefficient	Standard uncertainty (%)
Field source						
Non-uniformity of the field	Operator's judgement	0	Normal	1	1	0
Measurement equipment						
Calibration uncertainty	Calibration certificate	1	Normal	2	1	0.5
Uncertainty of the field meter/probe	Manufacturer data sheet	3	Rectangular	$\sqrt{3}$	1	1.73
Noise	Manufacturer data sheet	0	Normal	1	1	0
Measurement procedure						
Positioning uncertainty of the probe	Operator's judgement	≈0	Rectangular	$\sqrt{3}$	1	0
Uncertainty due to orientation of the probe	Operator's judgement	≈0	Rectangular	$\sqrt{3}$	1	0
Environmental conditions						
Temperature and humidity	Manufacturer data sheet	0	Rectangular	$\sqrt{3}$	1	0
Proximity effects of the operator	Operator's judgement	0	Rectangular	$\sqrt{3}$	1	0
Proximity effects of objects	Operator's judgement	0–5	Rectangular	$\sqrt{3}$	1	0–2.89
Background fields	Operator's judgement	0–15	Normal	2	1	0–7.5
Combined standard uncertainty, $u_c = \left(\sum u_i^2\right)^{1/2}$ (%)						1.80–8.24
Expanded uncertainty (normal distribution), $U_B = k \cdot u_c$ (for k=2)						3.60–16.47

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The measurement uncertainty was calculated for all measurement locations and overall was found to be within 3.60–16.47 % for magnetic field measurements and 3.60–11.21 % for electric field measurements. The maximum values of the total uncertainty for both electric and magnetic field measurements were obtained by combining the maximum values of the uncertainty contributions. When measuring the power frequency electric or magnetic field near an overhead transmission line, some factors (e.g. proximity effects of objects and background fields) significantly contribute to the total uncertainty, while others (e.g. temperature and humidity) are negligible. Particularly, the following observations were noted in accordance with data from both Tables 3 and 4:

(1) The maximum uncertainty value of the background field results when the field level from the overhead transmission line approaches the value of the background field (e.g. at measurement points nearby power distribution lines or equipment).
(2) In the case of electric field strength measurements, the maximum uncertainty value due to proximity effects of the objects occurs at measurement points nearby obstacles, such as lighting masts, fences, trees, utility poles, etc. In the case of magnetic flux density measurements, the maximum value occurs exclusively at measurement points nearby metal objects, as lighting masts, fences, vehicles, etc.
(3) The value of uncertainty due to proximity effects of the observer is based on related Standards[7,9] for 5-m distance between the field meter and operator. For larger distances the proximity effects have negligible impact.
(4) The influence of temperature and humidity is not taken into account, because the measurements are performed within the specified operating temperature and relative humidity ranges.
(5) The uncertainty of the instrument from noise floor in electric and magnetic field measurements is considered negligible because the noise level is 0.14 V m^{-1} and 0.8 nT, respectively[16]. These values are considered negligible.
(6) The uncertainty value due to non-uniformity of the field and errors in positioning and orientation of the probe are almost negligible because beneath high-voltage overhead lines, electric and magnetic fields are generally uniform[8].
(7) Other contributions, previously listed in Table 1, have not been taken into account in these specific cases, because they are not significant with respect to those reported in Tables 3 and 4.
(8) The person, who performed the measurement, plays an important role in the estimation of overall uncertainty. Several uncertainty components such as the proximity effects, background fields, errors in positioning and orientation of the probe are determined by operator.

In the below paragraphs, the overall estimate of measurement uncertainty depending on the type of measurement area is presented.

Residential area

Besides the uncertainty associated with the use of a field meter, other contributions also have to be considered when evaluating uncertainty of a field measurement in residential environments. These contributions depend on the measurement procedures, environmental conditions and characteristics of the field source. In the case of power frequency field measurement near an overhead transmission line, high uncertainties can mainly occur when measuring highly non-uniform fields close to other sources of power frequency fields and obstacles. Specifically, in the case of electric field measurements, it is clear that the most significant contribution is the presence of nearby metal objects or structures, for example, when performing a measurement in proximity to a vehicle or fence. On the contrary, in the case of magnetic field measurement, the dominant contribution is the presence of a background magnetic field, when its value approaches the field level from the overhead line. In addition, if a spot measurement at a measurement point near other sources of power frequency magnetic field is performed, sometimes it will be impossible to specify with confidence the uncertainty without additional information about them (e.g. current load, location relative to the measurement point, etc.). The presence of ferromagnetic or conductive objects in the proximity of the probe is also known as one of the obviously largest sources of uncertainties for magnetic field measurements.

Next, the measuring uncertainties at each measurement line of the above-mentioned example are shown in Figures 7 and 8. In this example, the measurements are characterised by very high uncertainty values compared with the ones usually related to other field measurements. Measurement uncertainty varies with the measurement point and the measurement line. At some measurement points the measuring uncertainty was estimated between 10 and 12.5 % due to the presence of other nearby circuits and objects. However, in the absence of nearby objects (uncertainty due to proximity effects of objects=0) and overhead distribution lines (uncertainty due to background fields=0), the expanded uncertainty of the measured field values are only associated with the instrument and computed by means of the instrument characteristics in accordance with Tables 3 and 4.

In particular, as shown in Figure 7, the total measurement uncertainty for electric field is increased by the presence of buildings, fences and cars located very close at the measurement points from −100 to 40 m. As the measurement points are moved away from this area, the total measurement uncertainty is essentially

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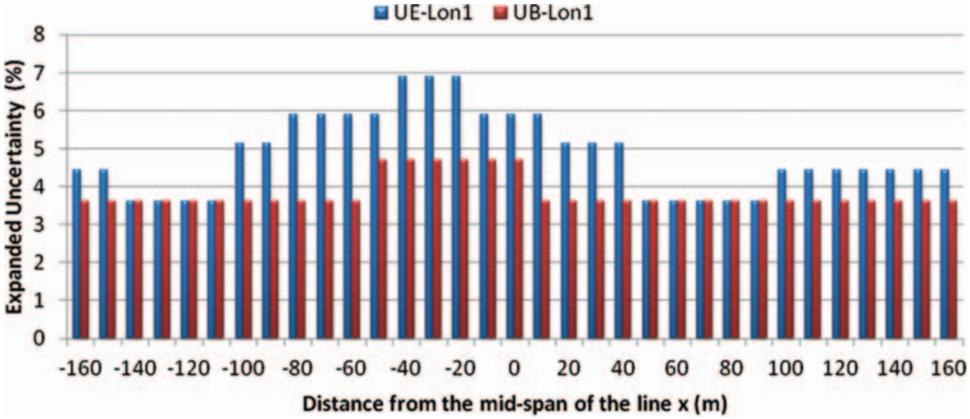

Figure 7. Total uncertainty of electric and magnetic field measurements in measurement line Lon-1.

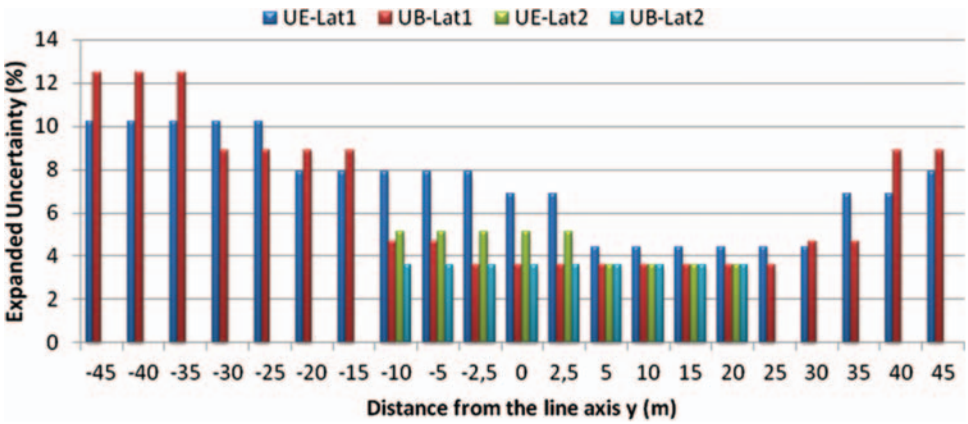

Figure 8. Total uncertainty of electric and magnetic field measurements in measurement lines Lat-1 and Lat-2.

reduced to 3.60 %. However, the total measurement uncertainty is increased near the steel towers because of tall grass. On the other hand, the highest total measurement uncertainty for the magnetic field is observed at the measurement points from −50 m to 0 m because of distribution line's magnetic field. For the rest of the measurement points, the total measurement uncertainty is decreased to 3.60 %.

As it can be seen in Figure 8, the total measurement uncertainty for electric field varies from 3.60 to 10.23 % at measurement line Lat-1. Specifically, high uncertainties (higher than 10 %) are observed for several metres from −45 to −2.5 m away from the line axis, because measurement points are close to buildings, lighting masts and trees. Also, the estimated uncertainty is increased at the right side of the profile because of a 3-m high fence. Moreover, the total measurement uncertainty for magnetic field varies from 3.60 to 12.47 %. The maximum value of measurement uncertainty occurs due to a medium voltage distribution line. Also, at the right side of the profile the uncertainty estimation is affected by the field of a low-voltage distribution line. Between −10 m and 35 m the total measurement uncertainty has the minimum value.

In the opposite, at the measurement line Lat-2 the total uncertainty is small for both electric and magnetic fields, because the values of the electric field strength and magnetic flux density are not considerably affected due to the absence of nearby objects. Only the total uncertainty for electric field reaches 5.2 % due to the influence of vegetation on the electric field strength.

Open land

The measurement uncertainty during practical outdoor measurements is typically near 10 %,

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although this value is reduced in some areas. In the case of electromagnetic field measurements at open lands the number of parameters affecting accuracy of the field measurements is very small. The only uncertainty source is uncertainty associated with the use of the field meter, which includes the components due to absolute error (calibration), frequency response, linearity, isotropic deviation (anisotropy), temperature and relative humidity. Thus, the value for this uncertainty is set equal to the instrumentation uncertainty (3.60 % for both electric and magnetic field measurements). In this case, it is assumed that no other power lines or objects were located nearby and the earth surface was flat. Also, the influence of the perturbation introduced by the observer is taken into account to be negligible in the above discussion.

Hilly or mountainous regions

In these areas, the resulting uncertainty is strongly dependent on the measurement point and it becomes more critical in close proximity to trees and tall grass, because of the strong non-uniformity of the electric field. Except this significant influence of vegetation on the electric field strength, errors in positioning of the probe must be considered, when the terrain is not flat enough. In the opposite, the total uncertainty of the magnetic field measurement remains nearly constant.

However, if the current flowing through a power line is very low (e.g. generated by a wind farm at low wind speed) a problem on uncertainty estimation of magnetic field measurement will occur. In this case, if the measured value is lower than the limit of field meter's dynamic range, there is a strong probability that the measurement uncertainty will be higher than the one specified by the manufacturer. Nevertheless, this unknown value is of little importance as the measured magnetic field level definitely complies with the safety limits.

CONCLUSIONS

Measurements were conducted in the vicinity of high-voltage power lines, aimed at identifying and quantifying the measurement uncertainty components, and later calculating the total measurement uncertainty. Appropriate equipment and measurement procedure achieving a satisfactory recording of the field values and keeping the uncertainties small were, first, described. Although, many parameters affect the accuracy of electric and magnetic field measurements, depending on the type of measurement site. Therefore, it is necessary to use a proper estimation technique based on related Guides and Standards for each measurement area after identifying the uncertainty components of the power frequency field measurements.

In the paper the calculation of these uncertainties was described taking under consideration certain uncertainty sources of Type B. A complete numerical application considering the equipment data (manufacturer data sheet and calibration certificates), environmental conditions, characteristics of the field source and measurement procedure of the HVLab of the NTUA was, also, presented. Because of all these uncertainty components the total measurement uncertainty values can exceed 10 %, although this value can be reduced under controlled conditions. The presence of objects in the proximity of the probe and the presence of magnetic background fields are the most significant contributions to the uncertainty for electric and magnetic field measurement, respectively. Also, it is clear that the total measurement uncertainty is remarkably influenced by the operator's judgement.

Further work should be considered in order to reduce the uncertainties presented here to ensure sufficient measurement accuracy.

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